



LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-JC-155485

Proposed Specification of EUVL Mask Substrate Roughness

E. Gullikson, C. Walton, and T. Taylor

September 26, 2003

2nd International Symposium on EUVL, Antwerp, Belgium,
September 30 – October 3, 2003

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

This report has been reproduced directly from the best available copy.

Available electronically at <http://www.doc.gov/bridge>

Available for a processing fee to U.S. Department of Energy
And its contractors in paper from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-mail: reports@adonis.osti.gov

Available for the sale to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-mail: orders@ntis.fedworld.gov
Online ordering: <http://www.ntis.gov/ordering.htm>

OR

Lawrence Livermore National Laboratory
Technical Information Department's Digital Library
<http://www.llnl.gov/tid/Library.html>

Proposed specification of EUVL mask substrate roughness

Eric Gullikson

Lawrence Berkeley National Laboratory
Berkeley, CA 94720

Chris Walton, John Taylor

Lawrence Livermore National Laboratory
Livermore, CA 94550

A revised specification of mask substrate roughness was proposed at the 1st International EUVL Symposium in Dallas in 2002 [1]. This document describes the reasoning behind the proposed revision in more detail.

The specification of mask substrate roughness should be based on its effect on lithographic performance. The effects of mask roughness can be considered according to the spatial frequency. At high frequencies ($f > M \times NA / \lambda$) corresponding to spatial periods too small to be resolved, light is scattered outside the angular acceptance of the camera effectively reducing the reflectivity of the mask. At lower frequencies, $f < M \times NA / \lambda$, light is scattered within the acceptance angle of the camera and can degrade the aerial image quality.

The loss in reflectivity due to high-spatial frequency roughness (HSFR) is given by

$$R / R_0 = \exp(-(4ps / l)^2), \quad (1)$$

where R_0 is the peak reflectivity of the coating on a smooth substrate, σ is the HSFR after multilayer coating. The relationship between top surface roughness and substrate roughness depends on the multilayer deposition process and significant smoothing of substrate roughness has been demonstrated [2]. Ultimately the specification of HSFR may be best decided based on the multilayer deposition process. For the present we may adopt a worst-case scenario of no smoothing in which case the top surface roughness is the same as that of the substrate. At very high spatial frequencies, light scattered from the individual interfaces of the multilayer coating no longer adds in phase and the effect of the roughness is diminished. For a typical Mo/Si multilayer coating this occurs at a scattering angle of about 15 degrees from specular and corresponding spatial-frequency of 0.02/nm (50 nm spatial period). If a 2% (relative) loss in reflectivity is allowed due to the HSFR of the mask substrate then one arrives at the following specification,

$$\text{HSFR} < 0.15 \text{ nm} \quad (0.004 / \text{nm} < f < 0.02 / \text{nm}). \quad (2)$$

The low frequency limit is $M \times NA / \lambda$ rounded down to 0.004/nm (250 nm spatial period), where the magnification $M=0.25$, $NA=0.25$ and $\lambda=13.5 \text{ nm}$.

Roughness with spatial frequencies less than MNA/λ scatters light within the acceptance aperture of the camera. In the case of the optics this mid-spatial frequency roughness (MSFR) is the major cause of flare in an EUV lithographic camera. In the case of the mask this roughness results in random phase variations in the aerial image. These phase variations, when coupled with defocus, can result in speckle and line edge roughness (LER) or line width roughness (LWR) for short spatial periods and image placement errors (IPE) for longer spatial periods. These effects are more easily related to the rms surface slope than to surface height errors. From geometric optics, a local slope error σ_s will lead to an image shift of

$$\Delta = 2\sigma_s z / M, \quad (3)$$

where z is the defocus distance at the wafer.

Consider first the high spatial frequency slope errors leading to LWR. For a rough surface with an rms slope error of σ_s the random displacements lead to

$$LWR = 3\sqrt{2}(\sigma_s)z / M. \quad (4)$$

The factor of 3 is there since LWR is typically a 3-sigma value. The factor of $\sqrt{2}$ assumes that the displacements of the two edges of the line are uncorrelated. For typical substrates it is found that the spatial periods near the camera resolution are the most important contributors to the rms slope error. Since the low frequency limit is less critical a frequency range of $0.1M \times NA/\lambda$ to $M \times NA/\lambda$ could be used for the high-frequency slope error. This choice has the advantage that the rms slope error over this frequency range can be determined from AFM measurements at selected points on the mask substrate.

The allowable LWR should be small enough that no randomly occurring printable defects are allowed over the area of the mask. For a resolution element of $\lambda/(M \times NA) = 216$ nm on the mask and a quality area of dimension $L = 142$ mm, the probability of a line width fluctuation large enough to cause a printable defect should be

$$P < \left(\frac{L}{M \cdot NA \cdot L} \right)^2 = 2 \times 10^{-12} \quad (5)$$

Assuming Gaussian statistics, the rms line width fluctuation should be 1/7 of the size of a printable defect which for a 10% $\Delta CD/CD$ printability criterion the required $LWR < 0.04 \times CD$. So for example, for a 32 nm line with a ± 90 nm depth of focus, the $LWR < 1.3$ nm and the specification for high frequency mask slope error would be

$$\sigma_s < \frac{M \cdot LWR}{6z\sqrt{2}} = 0.4 \text{ mrad} \quad (0.0004 / \text{nm} < f < 0.004 / \text{nm}). \quad (6)$$

The rms slope error for this frequency range could be calculated from an AFM measurement with a scan size of 5 microns. The rms slope can be obtained from the calculated PSD by,

$$s_s^2 = \int_{f_{\min}}^{f_{\max}} (2\pi f)^3 \text{PSD}(f) df \quad (7)$$

Where $f_{\min} = 0.0004/\text{nm}$ and $f_{\max} = 0.004/\text{nm}$. The HSFR can also be determined from the same AFM scan if the step size is smaller than 25 nm.

It is important to note that the LWR produced by high frequency mask slope errors will also depend on the partial coherence of the illumination. The high frequency slope error specification could be relaxed for higher values of the partial coherence σ .

Finally at lower frequencies mask slope errors result in image placement errors according to equation (3). For example, if the allowable 3-sigma IPE = 1 nm then the allowable low frequency rms (1-sigma) slope error spec would be

$$s_s < \frac{M \cdot \text{IPE}}{6z} = 0.5 \text{ mrad} \quad (10^{-6} / \text{nm} < f < 0.0004 / \text{nm}). \quad (8)$$

This spatial frequency range corresponds to spatial periods between 2.5 microns and 1 mm. An issue for this range is whether or not it is acceptable to sample the surface roughness at a few points on the mask as is typically done for optical surfaces or whether the entire surface of the mask needs to be inspected for slope errors. The rms slope errors over this frequency range could be determined statistically from roughness measurements using an interference microscope at selected points on the mask surface. Spatial periods longer than 1 mm would be covered by the mask flatness specification.

[1] E.M. Gullikson, J. Taylor, K. Blaedel, S. Baker, C. Larson, *1st International EUVL Symposium*, Dallas, TX 2002.

[2] E. Spiller, S.L. Baker, P.B. Mirkarimi, V. Sperry, E.M. Gullikson, D.G. Stearns, *Appl. Opt.* **42**, 4049 (July 2003).

Work performed for DOE by UC, LLNL under contract No. W-7405-Eng-48.